

An Overview of NASA's Activities in Micro-Nano Technologies

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NASA's Cross Enterprise Technology Development Program

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Abstract

An Overview of NASA's Activities in Micro-Nano Technologies

An examination of how mass is used in spacecraft design indicates that technology efforts directed only to reduce the mass of electronics, both digital and analog, will not significantly reduce the mass of a spacecraft, regardless of how much success those efforts achieve. Instead work to reduce the mass of electronic packaging, cabling, and connectors by taking advantage of higher levels of integration and three-dimensional design is necessary. To effect this design approach reduced power dissipation, improved thermal conduction, and improvements in specific power generation and specific energy storage are essential elements of NASA's micro-technology program. Because the fraction of a spacecraft's mass used for conducting and radiating waste heat is relatively large and because a large fraction of that waste heat is produced by the RF communications system, advanced technology work to reduce the amount of energy required by the communications system, by improving data compression, by improving the efficiency of the communications system, or by producing light-weight apertures are important steps toward truly lightweight spacecraft.

Even as these technology directions at the "micro" level are being pursued, the United States has begun a National Nanotechnology Initiative, in which NASA is a key participant. As micro-technology matures, it is expected that over the next five years, nano-technology research will become one of the principal elements of the fundamental technology investigations being conducted by NASA and that NASA's efforts in micro-technologies will become more directly focused on the needs of specific missions.

Discussion Topics

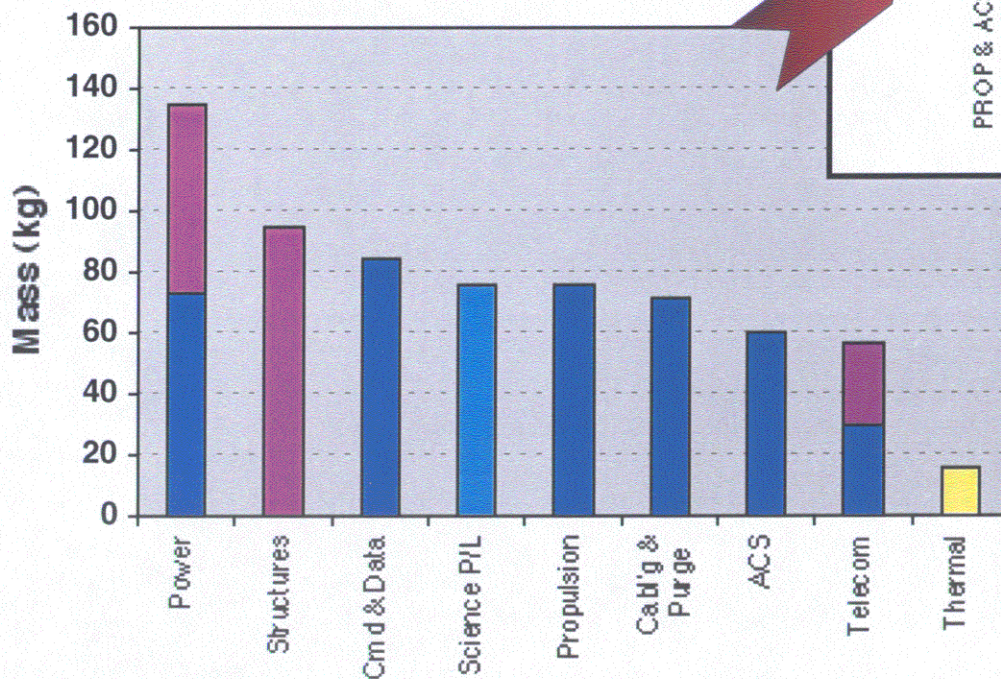
- **Advanced Technology Needs and Goals**
- **Current NASA Activities**
- **Future Plans**

Spacecraft Miniaturization Presents System Challenges

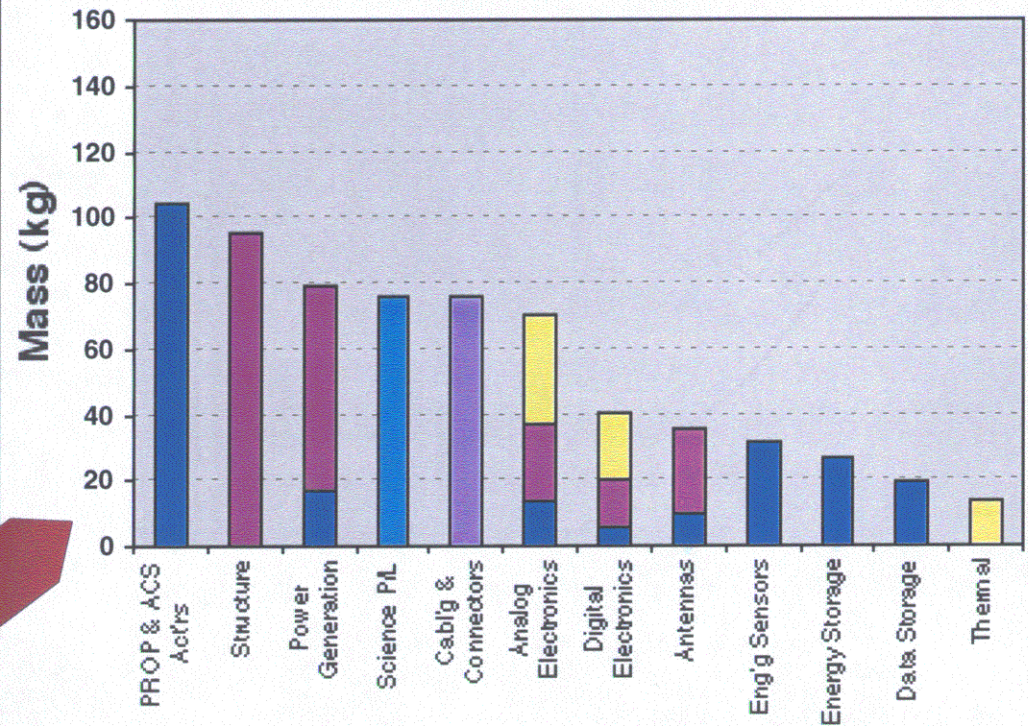
- **Past technology investments addressed a limited set of technical issues**
 - **Largely in μ -electronics**
 - Increased integration
 - Reduced power
 - Radiation hardness
 - **Less attention paid to more “mechanical” elements of the spacecraft**
- **But, the objective is to reduce the mass of spacecraft, a systems issue that presents a set of complex relationships**
 - **Thermal**
 - **Power**
 - **Propulsion dry mass**

The Nature of Spacecraft Mass Reduction Depends on Point of View

Traditional Subsystems



Functional Elements



For Mars Global Surveyor

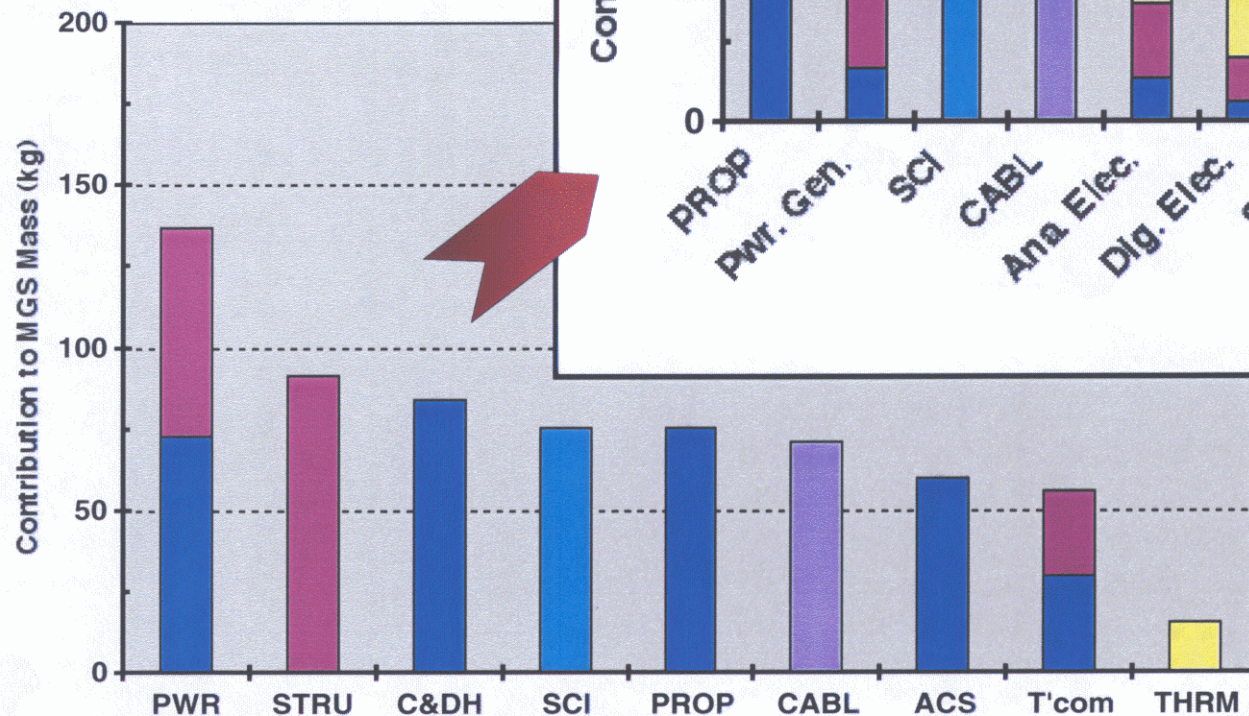
- Largest masses are actually dependent variables
 - Prop, ACS actuators, Structure, and Power
- Other masses are driven more by packaging, cabling, and thermal control masses than by that of electronics themselves

Mass Distribution of Mars Climate Orbiter Tells the Same Tale as That of Mars Global Surveyor

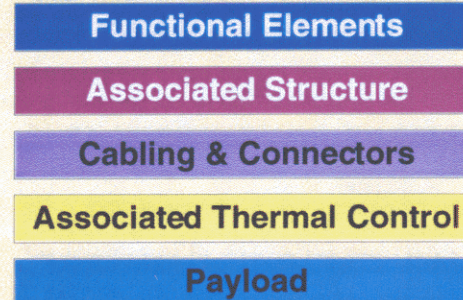
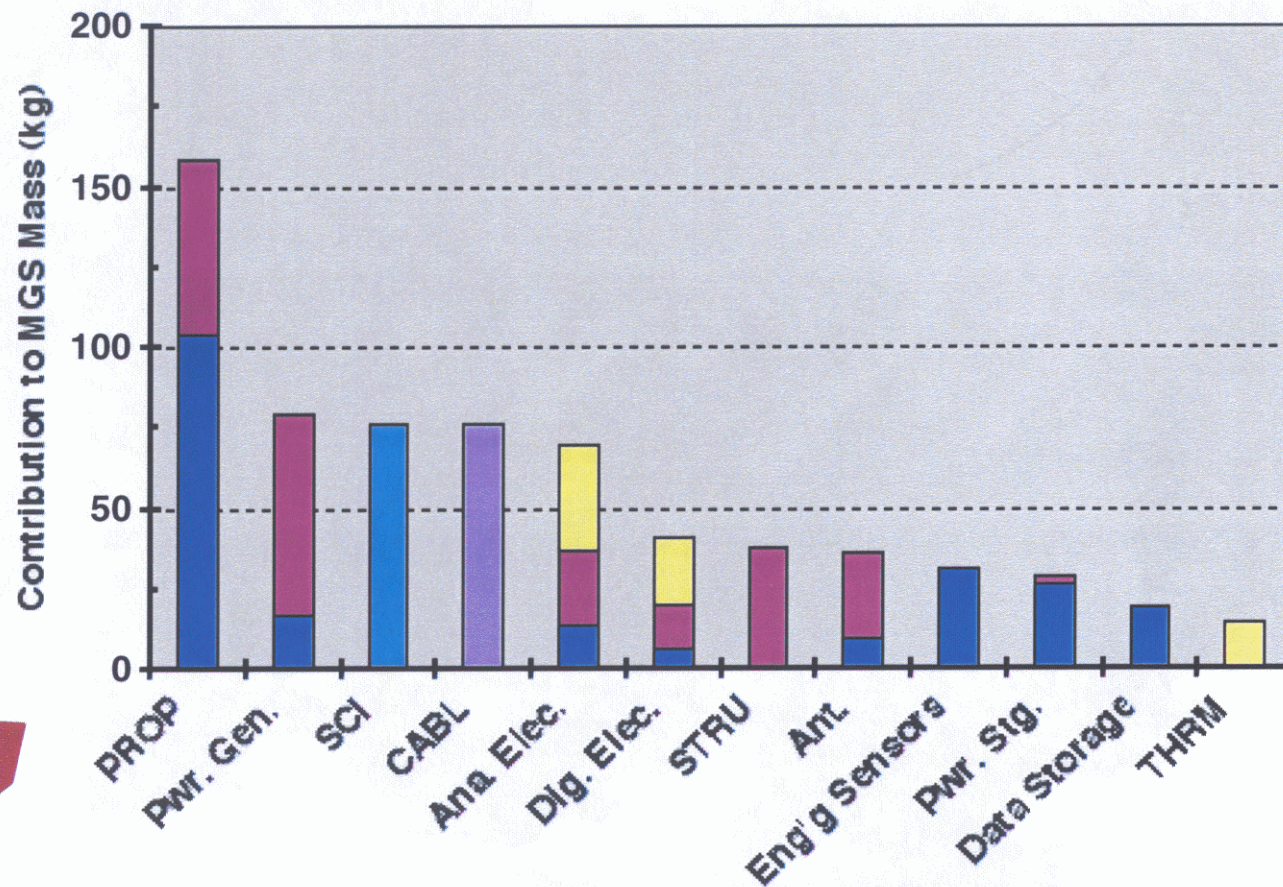
- **As with MGS, an examination of MCO masses shows:**
 - **Analog and digital electronics required almost negligible mass**
 - **Associated masses for structure and thermal control are significant.**
 - **Principal mass issues are “dependant” masses, proportional to the total system mass**
 - **Structure**
 - **Thermal control - driven by dissipated electrical power**
 - **Propulsion dry mass**
- **These evaluations can be used to establish technology goals**
 - **Ultra-Low Power digital electronics**
 - **More efficient analog circuits, especially for downlink signal processing**
 - **Improved structural integration**
 - **Multi-functional structures**
 - **Load carrying “black boxes”**
 - **Higher levels of integration to reduce cabling/connector requirements**
 - **System on a Chip**
 - **Integrated digital and analog circuits**
 - **3-D integrated circuits**
 - **Improved thermal control**
 - **Higher “effective” conductivity**
 - **Higher emissivity and variable emissivity**

Mars Climate Orbiter Tells the Same Tale

Traditional Subsystems



MCO Functional Elements

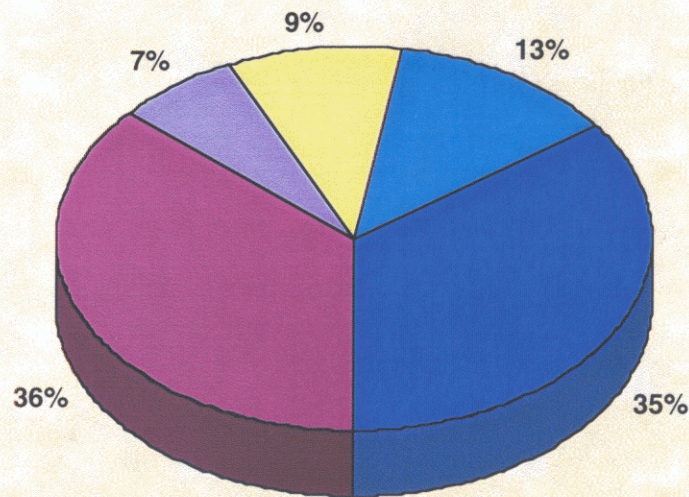


Despite the Difference in Size, the Distribution of Mass is Similar

- **Principal Observation: The distribution of mass for the two spacecraft is essentially the same despite:**
 - Factor of 2 difference in size
 - Decade between their σ C/D start dates
- **Examining the mass distributions for MCO and MGS allows several observations**
 - The mass associated with digital and analog electronics is small
 - The principal mass associated with electronics is that mass used to control the temperature of electronic modules, to support them structurally, and to connect them electrically
- **Thus, we are motivated to examine the following approaches to reduce spacecraft mass**
 - More functions on a single chip (e.g. System on a Chip) or 3-D integrated chips to eliminate cabling and connectors.
 - Integrate electronics and power into structure (multi-functional structure) or use “black boxes” as load-carrying structure to reduce structural mass.
 - Thermal technology advances to improve “effective” thermal conductivity (reduce conduction ΔT by a factor of 10) and to increase maximum thermal emissivity to reduce radiator size dramatically (factor of X).
 - More efficient use of power to reduce the amount of heat to be dissipated
 - Ultra-low-power technology for digital electronics
 - More efficient analog circuits
 - RF
 - PMAD
 - Power supplies

Despite the Difference in Size, the Distribution of Mass is Similar

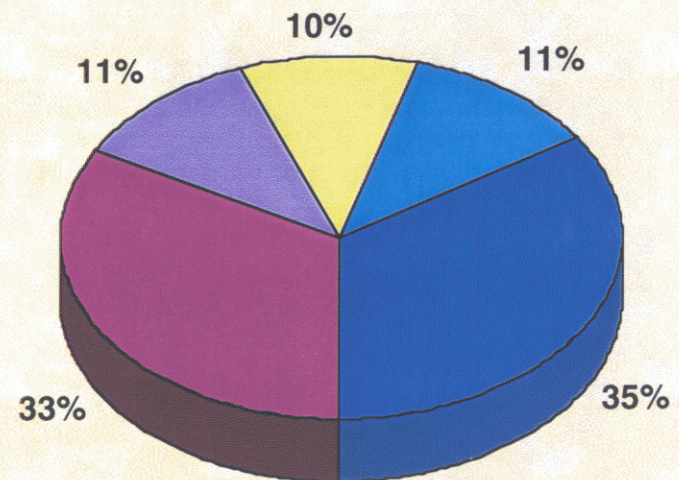
Mars Climate Orbiter



344.6 kg

(2.03% analog & digital electronics)

Mars Global Surveyor



666.5 kg

(2.93% analog and digital electronics)

Functional Elements

Cabling & Connectors

Payload

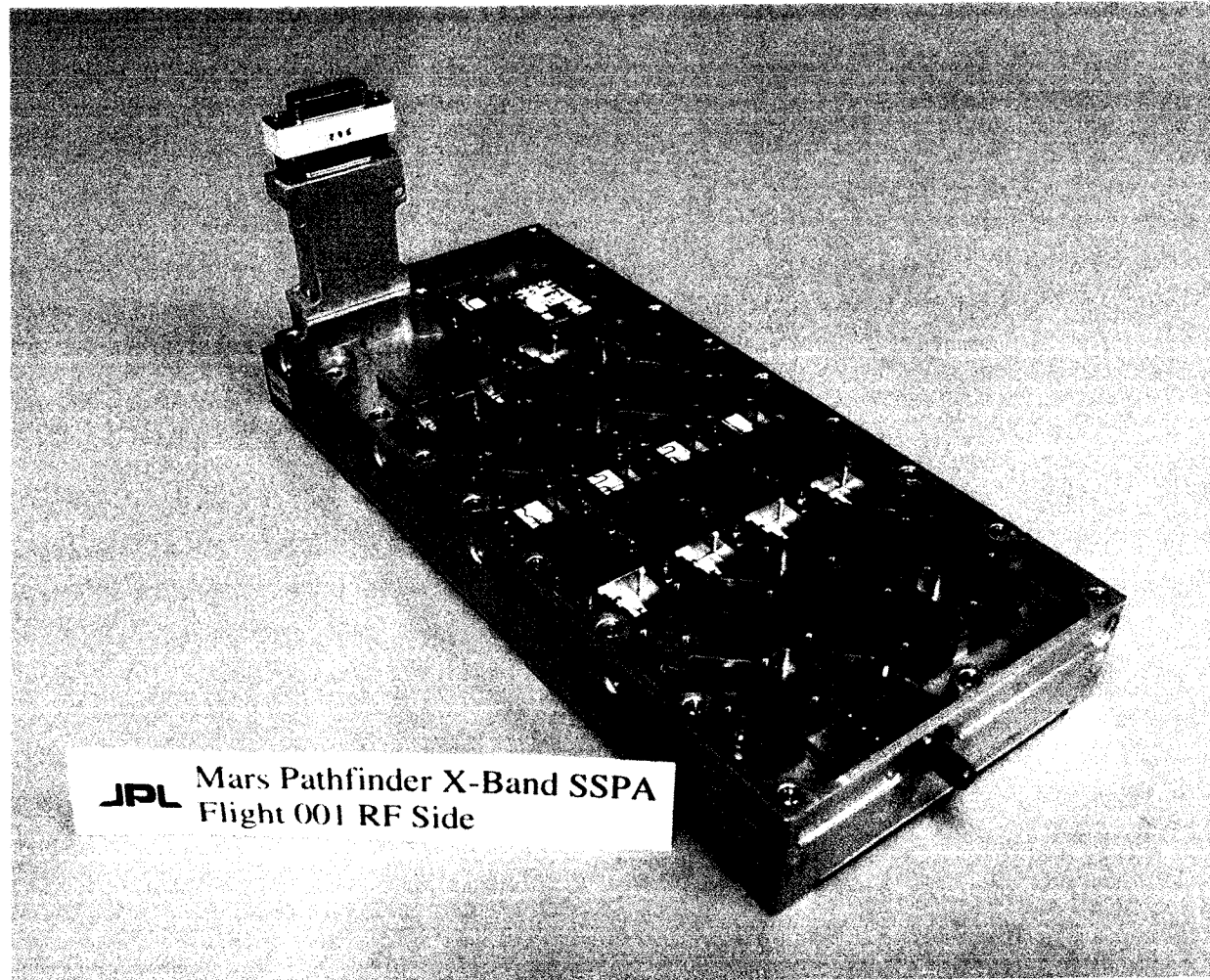
Associated Structure

Associated Thermal Control

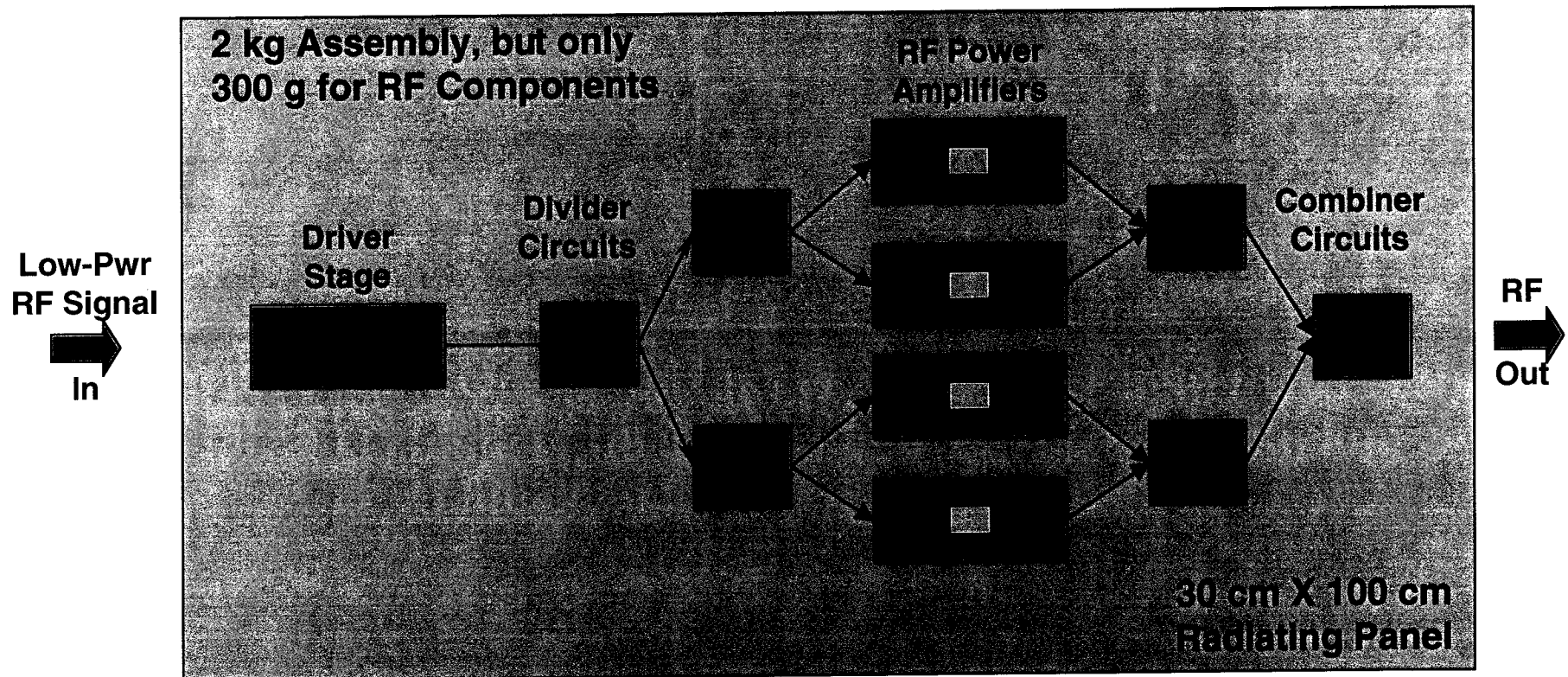
The DS1 RF Output Stage Illustrates the Systems Issues Associated with Spacecraft Mass Reduction

- **Of the 60 W input only 12 W is radiated as RF signal**
- **The remainder must be radiated as heat**
- **To maintain an allowable temperature (100 C) at the RF chips, four elements must be used instead of a single one**
 - **This requires several passive circuits to split and recombine the RF signal**
- **The mass increased from 300 g for the elements alone to 2,000 g when packaged because of the multitude of elements and the amount of heat to be radiated.**
 - **The packaging design, driven by thermal considerations, required a large radiating surface (30 cm X 100 cm) and thicker sections than needed to satisfy structural requirements alone**

DS1/Pathfinder X-Band Solid State Power Amplifier Illustrates Systems Nature of Technology Advances Needed To Reduce Spacecraft Mass



DS1 RF Output Stage Illustrates the Interdependency of Comm, Thermal, and Power Requirements

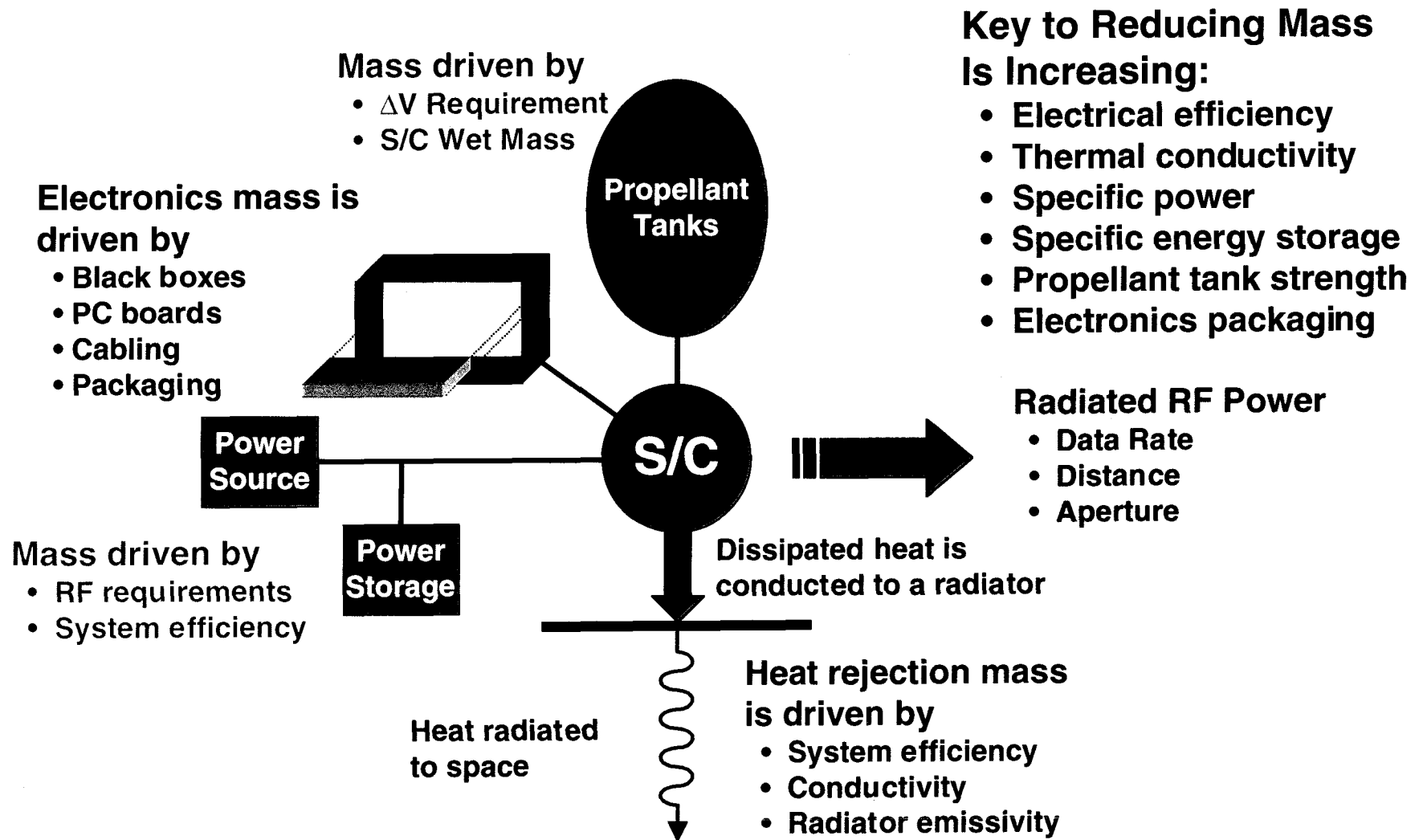


Smaller electronics is not always the path to lighter spacecraft. In this case, higher efficiency, improved thermal coupling, and reduced data rates are the remedies.

Technology Goal Setting Is Not Simply a Matter of Mandating Smaller Components

- **To reduce spacecraft mass an order of magnitude**
 - **Reduce RF power demands**
 - Reduce data rate with data compression
 - Increase aperture, perhaps using an inflatable antenna
 - **Improve electrical efficiency**
 - Ultra-low power designs for digital electronics
 - Smaller analog components
 - More efficient analog circuits
 - **Reduce heat rejection mass via improved thermal properties**
 - Improve Thermal Conductivity
 - Diamond films
 - Carbon nanotubes
 - active cooling
 - Higher emissivity surfaces
 - **Develop more mass efficient power generation and energy storage**
 - More efficient solar arrays
 - Improved electrochemistry
 - Use containers as load-carrying structure
 - **Reduce fraction of spacecraft used for propellant tank mass**
 - Linerless, high-strength fiber wrapped tanks
 - Make part of load-carrying structure
 - **Decrease the packaging mass associated with electronics**
 - Load-carrying black boxes or multi-functional structures
 - 3-D electronics, e.g. Systems on a Chip
 - Wireless data links

Reducing Spacecraft Mass Is Not Simply a Matter of Mandating Smaller Components



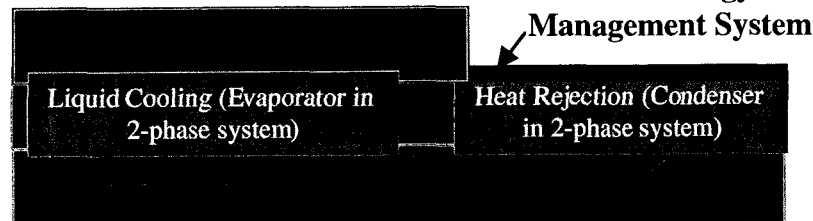
NASA's Current Activities

- **NASA's overall goal is to provide the needed, unique technology advances in micro-device technologies that will allow an order of magnitude reduction in spacecraft size or a corresponding increase in spacecraft capability**
 - **Cross Enterprise Technology Development Program**
 - **Ultra-Low-Power, radiation tolerant digital electronics**
 - **Mixed-signal integrated electronics**
 - **μ -Gyro**
 - **On-chip data compression**
 - **Linerless, fiber-wrapped propellant tanks**
 - **System on a Chip**
 - **μ -Communications**
 - **μ -Passive components**
 - **μ -Power sources**
 - **μ -ACS Sensors**
 - **μ -Device packaging**
 - **X-2000 — A focused technology program**
 - **Advanced technology μ -avionics for Europa Orbiter and Pluto Flyby**
 - **Long-lived, radiation hard (100 M-Rad), scalable avionics system**
 - **A core system for many future applications**

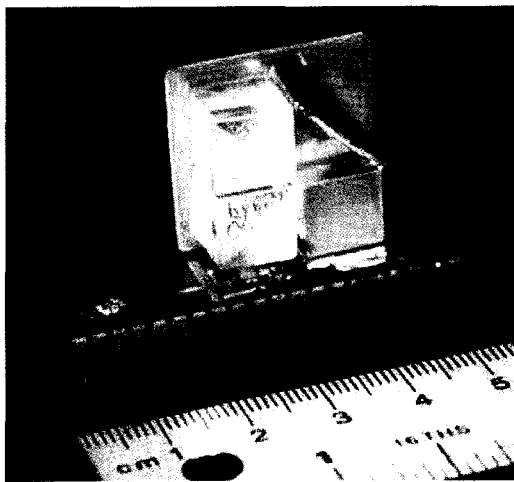
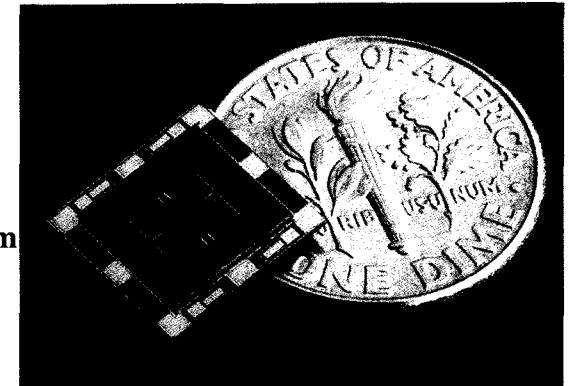
Current Activities by NASA Approach Mass Reduction from Many Different Directions

Common Goal: Establish the capability to reduce the mass of a spacecraft by a factor of ten, compared to the 1995 state of the art, by using the techniques of miniaturization to reduce both component size and the demands for spacecraft resources

On-Chip Liquid Cooling μ -Channels, μ -Pumps, and Integrated μ -Cooling System



Micro-Scale Gyroscope



Holographic Data Storage

19-21 September, 2000

μ -Electronics and MEMS can reduce spacecraft mass by improving packaging, thermal performance, and reducing power demands

- Reduce packaging and cabling mass by 3-D device designs, e.g. System on a Chip
- Reduce thermal mass by improved thermal conductivity between electronic heat sources and thermal radiators
- Reduce mass and power for data storage
- μ -Gyro and μ -Accelerometers reduce ACS sensor mass and power requirements

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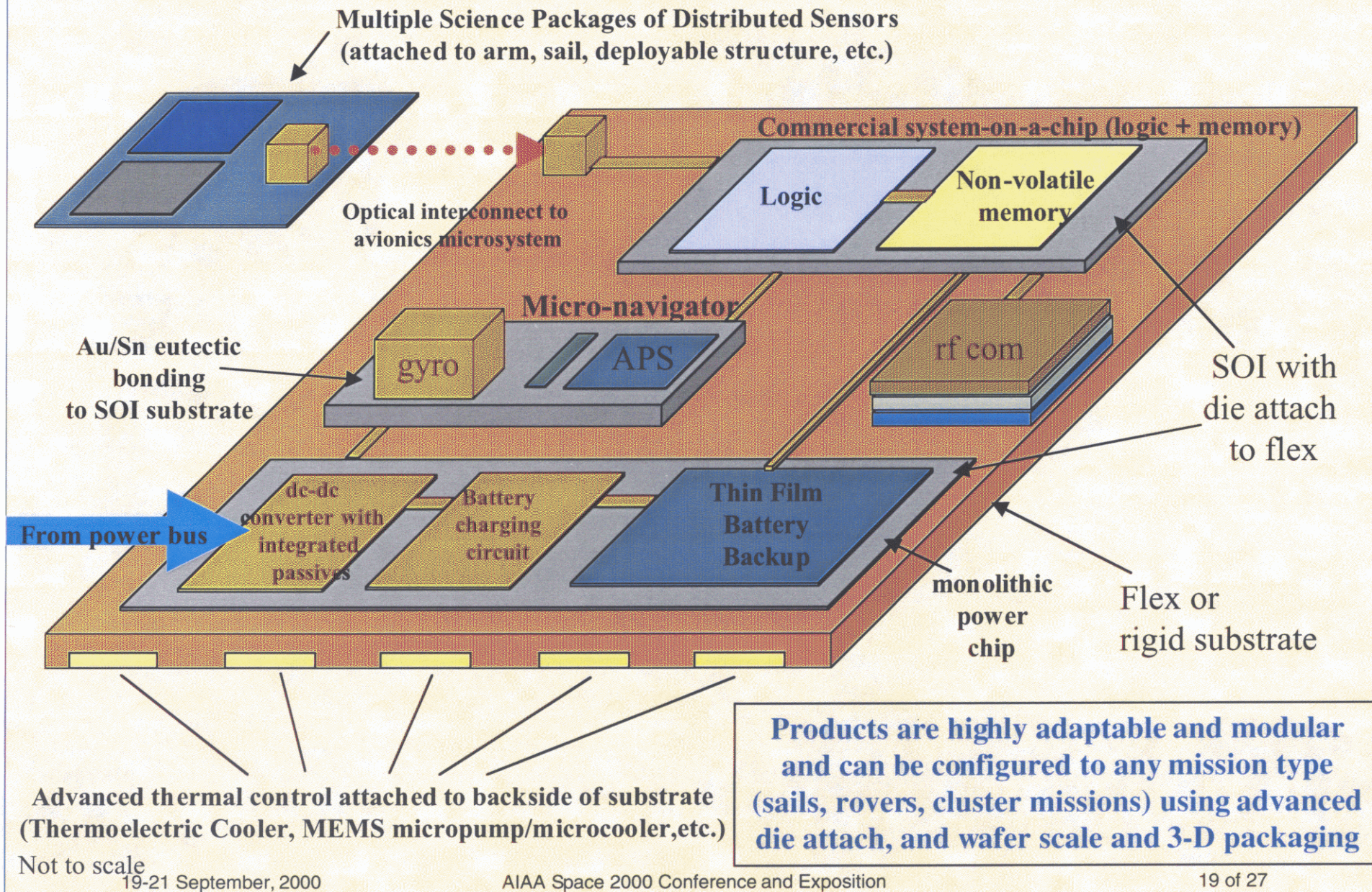
Avionics Micro-System

Enabled by SOAC Technology

- **System on a Chip (SOAC) is a NASA technology initiative and is part of the CISM* program**
- **SOAC is focused on establishing the capability to place the entire complement of a spacecraft's avionics package on a single chip**
- **Significant mass savings result**
 - **Reduced mass for ACS sensors**
 - **Reduced packaging and cabling mass**
 - **Reduced power dissipation**

*Center for Integrated Space Microelectronics

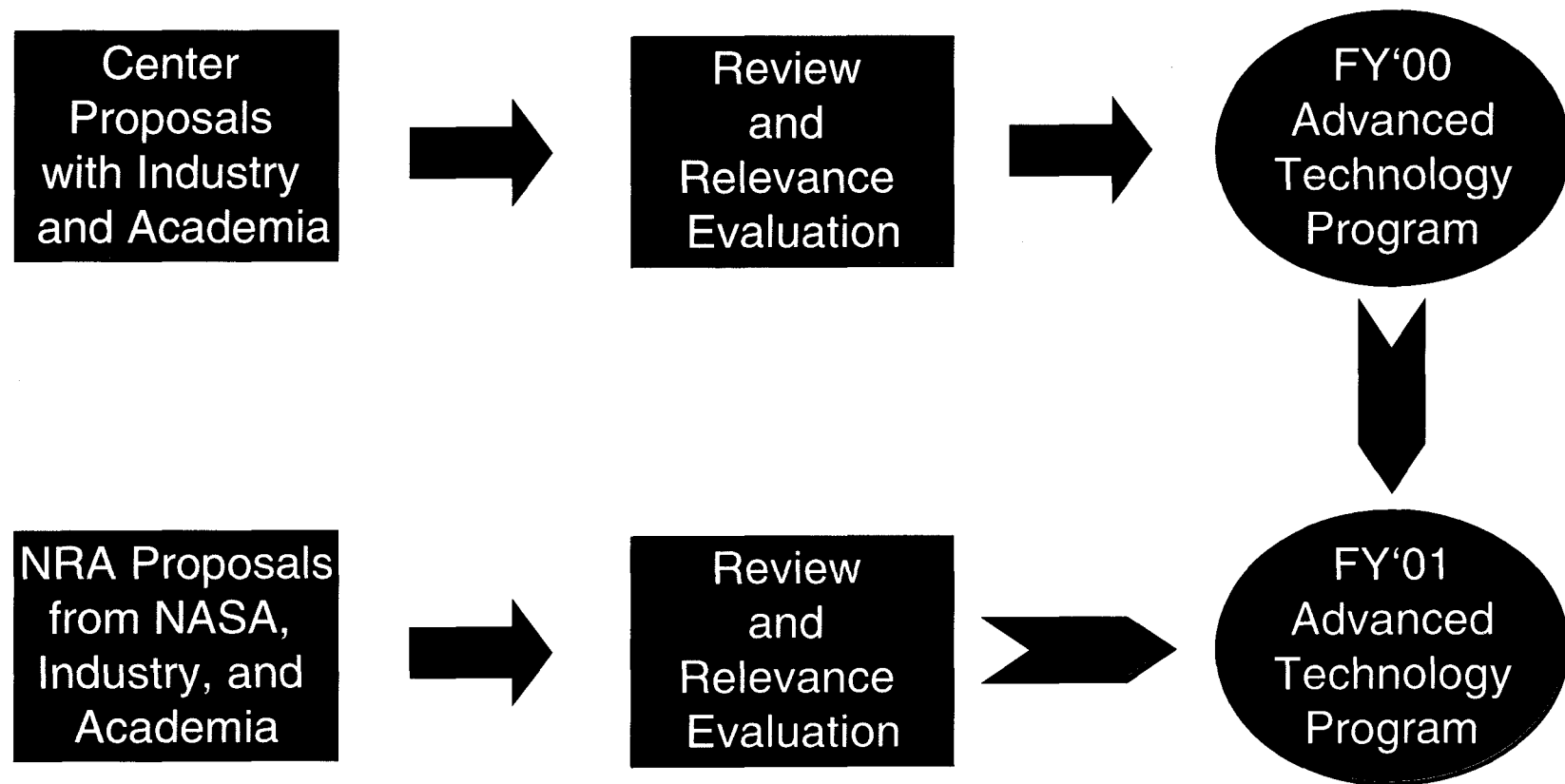
Avionics Microsystem enabled by SOAC technology



Independent Review and NRA Are Principal Elements Determining Content of NASA's Program

- **FY'00**
 - NASA Centers, working with industry and academia, prepared proposals for consideration for inclusion in the FY'00 program.
 - These proposals were reviewed for quality by an independent team from industry and academia and for relevance by representatives from NASA's Enterprises.
 - Proposals were solicited via NRA from NASA, other government agencies, industry, and academia for inclusion in the FY'01 program.
 - These proposals were reviewed for quality by an independent team from NASA and industry and for relevance by representatives from NASA's Enterprises.
- **FY'01**
 - Total program funding was decreased.
 - Also, the funding to continue the tasks begun in FY'00 was reduced to accommodate the tasks selected as a result of the NRA.
 - The resulting program is scheduled to be recommended to the selecting official on September 12-13, 2000.

Independent Review and NRA Are Principal Elements Determining Content of NASA's Program



NASA's Activities Are Part of a Larger National Effort

NASA's programs in micro-electronics and micro-devices are but a part of the activities being conducted in this area in the U. S. NASA's work is intended to support the needs of NASA's missions, both robotic and crewed.

In addition the U. S. Department of Defense supports substantial advanced technology activities in these areas.

All these activities, whether supported by NASA or by some other agency, all are directed toward improving the ability to making real the benefits of micro-technology.

NASA's Activities Are Part of a Larger National Effort

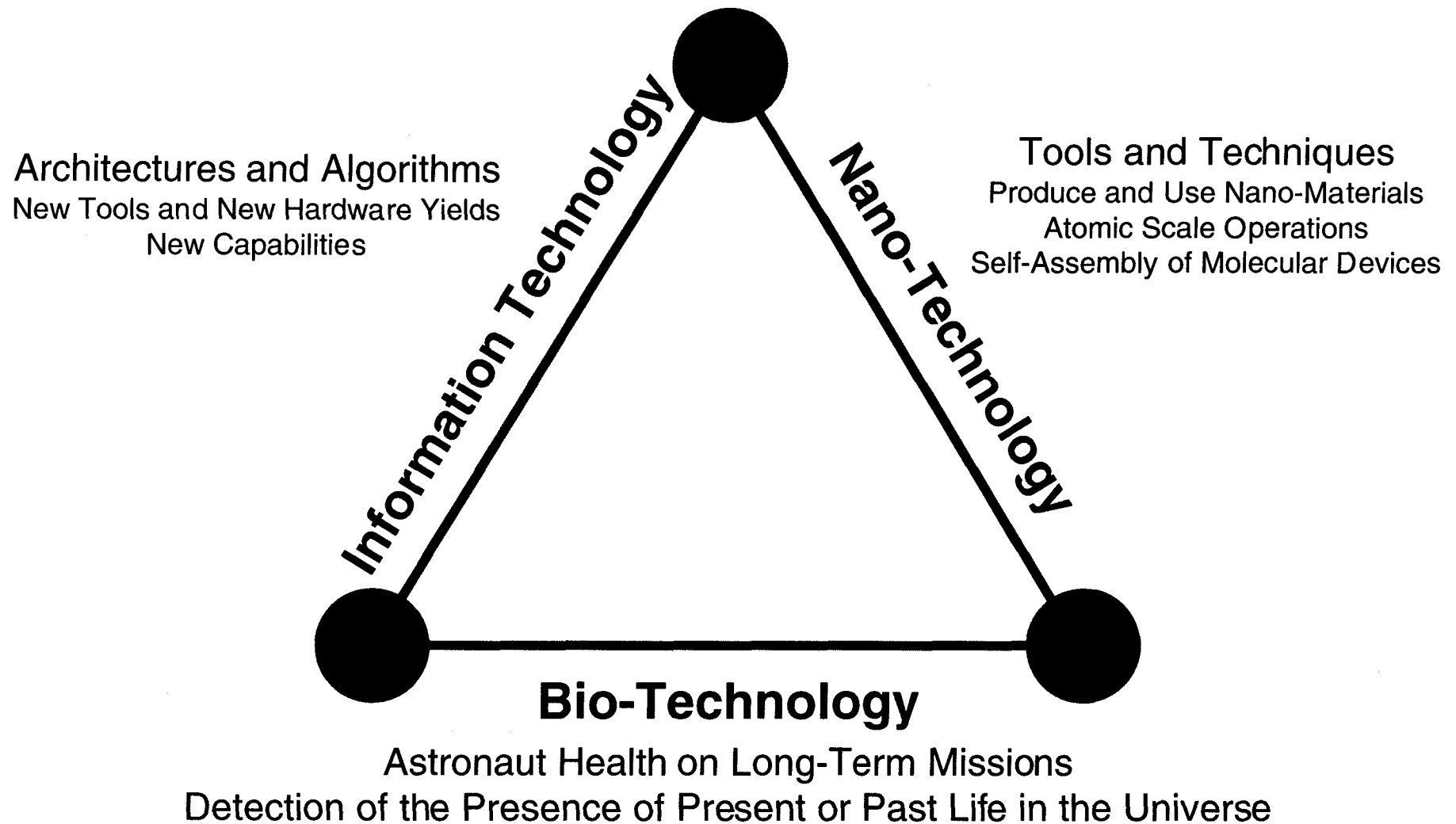
- **Almost every agency in the U. S. government that has technical responsibilities has a program in micro-devices.**
- **DARPA Microsystems Technology Office has one of the most extensive**
 - **Photonics**
 - **Electronics**
 - **Micro-Electromechanical Systems (MEMS)**
 - **Merge information processing with sensing and actuation to realize new systems and strategies to bring co-located perception and control to the physical, biological, and chemical environment.**
 - **Demonstrate key devices, processes and prototype systems using MEMS technologies**
 - **Develop and insert MEMS products into commercial and defense systems**
 - **Lower the barriers to access and commercialization by catalyzing an infrastructure that can support shared, multi-user design, fabrication, and testing**

NASA's Advanced Technology Initiatives

- **In 5 to 10 years, the technology advances associated with μ -electronics and MEMS are expected to have reached the point of diminishing returns**
- **Three new advanced technology initiatives will take the agency into the twenty-first century**
 - **Information Technology**
 - **Bio-Technology**
 - **Nano-Technology**
 - **NASA is one of the US agencies participating in the national nano-technology initiative headed by NIH**
- **Information Technology**
 - **Architectures and Algorithms**
 - **Enable new capabilities, e.g. active fault tolerance**
 - **Enabled by and enables new advanced hardware**
- **Bio-Technology**
 - **Detect presence of life in the universe, past or present**
 - **Maintain astronaut health on long-duration crewed missions**
- **Nano-Technology**
 - **≤ 100 nm**
 - **Build from atomic scale**
 - **Self-Assembly**

NASA's New Advanced Technology Initiatives

NASA's technological future lies in the synergistic relationship of these three initiatives



Future Directions

Changes in NASA's advanced technology programs precede changes in developed hardware by five years or more. At this writing the diminution of advanced technology activities in micro-devices, activities grounded in techniques pioneered in the early days of the microelectronics revolution, can be seen.

Though practical micro-devices based on these techniques will continue to be developed for decades to come, the focus of the advanced technology community is already beginning to shift to nanotechnology. Nanotechnology offers the promise of capabilities only dimly seen today. The potential of in vivo health monitoring, critical for the health of astronauts on long-duration space missions, is only one of the many possible capabilities that can be foreseen.

Today work is being pursued to fabricate nano-materials like nanotubes, molecular circuits, and self-assembled systems using the tools of biology and chemistry. Analyses are being conducted to help determine directions and techniques uses quantum mechanical models to predict properties and benefits. Experimental work to identify the approaches that will bear productive fruit are being pursued in laboratories and universities throughout the world.

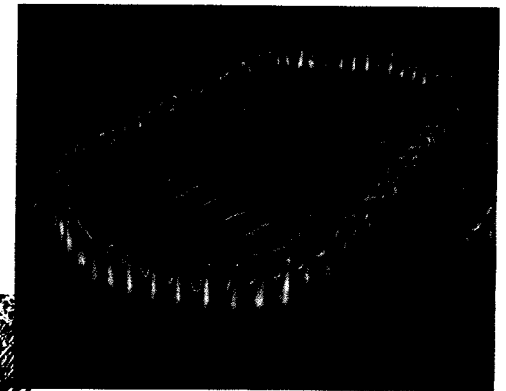
This investigative activity has borne enough fruit that the U. S. has begun a national nanotechnology initiative, headed by the U. S. National Institute of Health, in which NASA is a participant. This work will form the base on which NASA's future ability to explore space will be built.

Future Directions

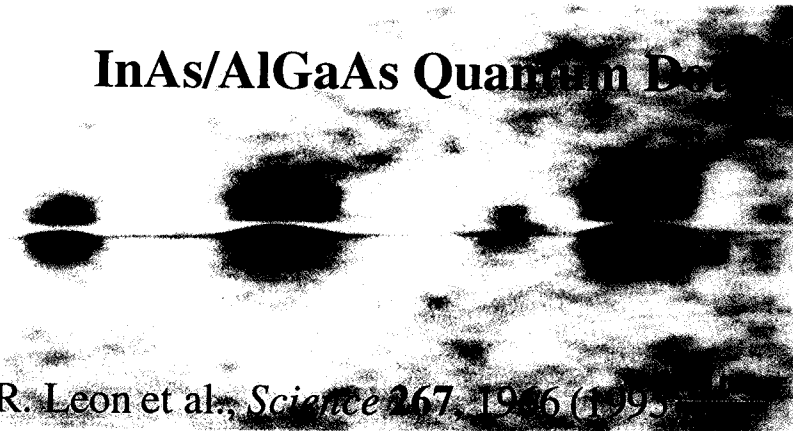
During the next five years expect:

- Advanced technology in μ -electronics and μ -devices to enable the development of spacecraft an order of magnitude less massive than those possible in 1995, while retaining the same functional capability
- Information technology advances will give those spacecraft capabilities far beyond that possible in 1995
- The first laboratory devices using nano-technology and nano-bio-technology will emerge
 - *In vivo* monitoring of astronaut health
 - Advanced materials based on carbon nanotubes
 - High strength
 - High thermal and electrical conductivity
 - Nano-electronic devices
 - Semiconductor properties of carbon nanotubes
 - Molecular circuits

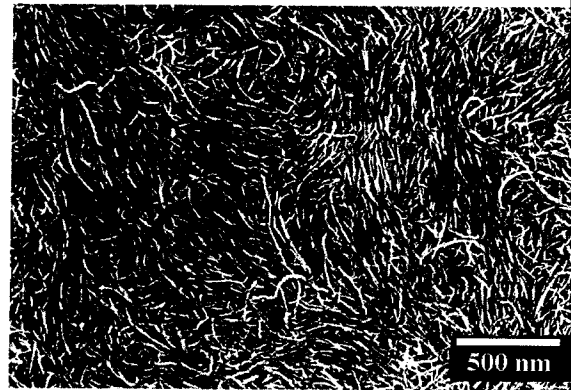
IBM's Precise
Atomic Placement



InAs/AlGaAs Quantum Dot



R. Leon et al., *Science* 267, 1946 (1995)



Carbon Nanotubes

